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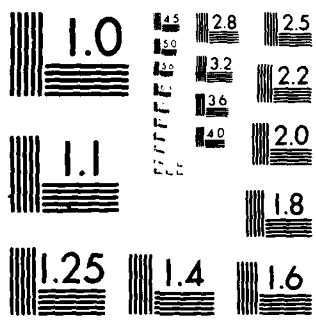

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FOREIGN TECHNOLOGY DIVISION

PROFESSOR M. M. PROTOD'YAKONOV'S STRENGTH COEFFICIENT f OF ROCKS

by

M. M. Protod'yakonov

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

EDITED TRANSLATION

FTD-ID(RS)T-1293-81 12 November 1981

MICROFICHE NR: FTD-81-C-001026

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By: M. M. Protod'yakonov

English pages: 37

Source: Voprosy Razrusheniya i Davleniya Gornykh Porod, Ugletekhizdat, Moscow, 1955, pp. 42-55

Country of origin: USSR
Translated by: Gale M. Weisenbarger
Requester: FTD/SDBF
Approved for public release; distribution unlimited.

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PROFESSOR M. M. PROTOD'YAKONOV'S STRENGTH COEFFICIENT f OF ROCKS

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The mechanical properties of rocks play a primary role in mining; on them depend the selection of the extraction method, the productivity of means of extraction, the behavior of the roof, and so forth.

Initially the mechanical properties of rocks were only evaluated qualitatively. Prof. M. M. Protod'yakonov, in one of his first works on this problem [1], characterized the approaches to study of the strength of rocks at the beginning of the XX century: "...in mining science it has long been the custom to determine not the absolute values of strength of rock, but only to compare rocks with each other, grouping them into known classes of strength, in that sense in which it is always understood, and to make these classes so broad

that it is easy to assign any given rock to one category or another. The attempts of this classification, however, suffer from complete lack of coordination because the authors, generally speaking, did not have as a goal the comparison of the strength, for example, with respect to drilling, with the strength with respect to settling of the surface and so forth and in addition the relationship between classes is only rarely expressed numerically and usually the authors are satisfied simply with the terms: "strong," "brittle" rocks and so forth."

But the development of mining urgently demanded a quantitative evaluation of the mechanical properties of rocks.

A famous Russian scientist, one of the founders of mining science, Prof. M. M. Protod'yakonov (1874-1930) was able for the first time to generalize all of this uncoordinated data and to establish objectively existing connections between various indices of mechanical properties of rocks and to establish the orderly study of the strength of rocks. This study was one of the bases of the further development of a number of very important divisions of mining science.

Prof. M. M. Protod'yakonov in his dissertation in 1907 [2], then in a report at a conference of scientists on mining, metallurgy and

machine building in 1910 [1], in a number of other works, and finally in a principal work in 1926 [3], established that the strength of rocks in various respects (with various methods of breakdown) are approximately identical and provided a general table of relative coefficients of strength f of all rocks. He suggested making this table the basis of calculating processes of recovering rocks and supporting workings. The coefficients of strength of rocks f have become widely known and have become firmly rooted in mining science and production.

During the past almost half a century repeated attempts have been made to refute the opinions of M. M. Protod'yakonov, but his teaching about the strength of rocks has found increasingly wider recognition and application in practice. Checking over a long period of time has shown the viability of the rock strength coefficients which he proposed.

Rock strength coefficients f are important for many branches of mining science: the science of the pressure of rocks, the science of the breakdown of rocks during their recovery, for technical standardization and etc.

In mining literature we encounter assertions that "strength" and "crushing strength" are synonyms and therefore it is necessary to use

the general technical term "crushing strength" in mining. Such assertions are incorrect and the suggestion to exclude the term "strength" is not acceptable. In fact, let us analyze carefully the content and range of application of both terms.

M. M. Protod'yakonov [3] defined the concept of strength of rocks as follows: "The strength of rock and of any material is its resistance to external forces."

The committee of technical terminology of the Academy of Sciences USSR [4] presently gives the following definition to the term "crushing strength": "crushing strength is the property of a material under certain conditions and within certain limits to receive those or other actions without crushing."

As we see, the term "crushing strength" refers only to those cases when the material is not crushed. In the definition of the term "strength," however, there is no such stipulation and therefore the latter term is applicable both for characterizing rocks with respect to their stability and with respect to their resistance to crushing during recovery. Further, the term "strength" is applied for any type of mechanical destruction, including such complex processes of destruction as notching, boring, breaking down, blasting, crushing, and so forth. The term "crushing strength," as a rule is used in

cases of determination of the temporary resistances to elongation, compression, bending, twisting, etc. Thus, by "crushing strength" we normally understand the resistance of a material to the action of only elementary stresses and not to all actions.

M. M. Protod'yakonov [1] wrote: "In everyday use by the word "rock strength" we have in mind, generally speaking, various concepts which in and of themselves are complex. Thus it is possible to talk about strength in the sense of greater or lesser ease of different types of recovery, i.e., resistance during drilling, during blasting or during direct recovery using those or other tools, for example a pick, shovel, and so forth. It is also possible to examine rocks with respect to their stability, also of a different type: when working, concerning supports, safety blocks, sinking of the day surface." "It is already evident from this how varied the concept of the strength of rock, and how dissimilar this concept is to those "elementary" concepts of resistance to compression, shear, or elongation which "structural mechanics" deals with.

From what has been presented above it follows that the content of concepts embodied in the terms "strength" and "crushing strength" are not identical and that the term "crushing strength" is not interchangeable with the term "strength."

As a measure of strength of rocks M. M. Protod'yakonov suggested a coefficient of strength, i.e., a dimensionless value indicating how many times stronger one rock is than another which is taken for one. It is interesting to trace how M. M. Protod'yakonov approached the development of strength coefficients and his famous scale of strength of rocks.

He first applied the coefficients of strength in 1907 for characterizing the stability of rocks and their pressure on mining supports [2]. M. M. Protod'yakonov considered that: "Rocks in mass are far from a continuous elastic body, such as they are usually considered in a course on the resistance of materials. A multitude of cracks, from microcracks to large ones, divide the entire mass into individual pieces and even there where a connection remains, it is significantly weaker than inisde of the pieces themselves." In addition he wrote: "It is obvious that the examined rocks also cannot be considered as truly disconnected (friable) bodies, because in the latter there exists only friction and here there is also a certain bond of the pieces with each other."

As is known, for characterizing friable bodies we use the coefficient of friction which is equal to the tangent of the angle of rest for these bodies. M. M. Protod'yakonov, by analogy, proposed for characterizing the stability of rocks that we use the apparant

coefficient of friction (coefficient of strength) equal to the tangent of the angle of rest in open mine workings. It is apparaent because it took into account not only the force of friction but also the force of adhesion of the pieces between each other. Later research by P. M. Tsimbarevich showed that the strength coefficients of M. M. Protod'yakonova are equal to the tangents of angles of internal resistance of the rocks, i.e. of angles at which the greatest stresses arise in rocks and at which cracks appear from the action of destructive forces.

Analyzing the shortcomings of the classifications of rock strength proposed before him, M. M. Protod'yakonov wrote: "Therefore my problem is first of all to reduce the different "types of strength" into a definite system and second, to establish a more rational classification and to express the relationship between classes in numbers" [1].

On the basis of theoretical considerations M. M. Protod'yakonov came to the following conclusion [1]: "Thus, if any rock is stronger than another in the ratio $f_1:f$ in any one sense (in our example, during drilling) then in any other (for example, supporting, sinking of the surface, blasting, etc.) it will be stronger in exactly the same ratio. Therefore the same classification may be established for all types of strength.

However, the actual rocks are not ideal bodies. Therefore the drawn conclusion can only be extended to them with a known error and the question immediately arises of its value; in other words it is necessary to determine whether we are not risking obtaining clearly inconsistent results."

Let us take characteristic rocks, place them in eight clsses and for completeness let us add another extreme class, water.

Let us now examine whether this table leads to any inconsistencies if we use it for all types of strength." Further M. M. Protod'yakonov writes: "...various persons, each for his own purposes, completely individually, established a classification of rocks with respect to strength; one for drilling, another for blasting operations, a third for sinking of the surface, a fourth for supporting, and so forth. No one had in mind comparing these tables. But it turns out that if we do this we obtain a fully explicit identity of classifications."

Then M. M. Protod'yakonov processed the data of a number of authors by replacing specific names of indices with dimensionless coefficients and all of the figures obtained in this manner he

reduced to a single common table, dividing the rocks into similar classes of strength:

"Now it remains to reduce the obtained figures of relative strength in such a variety of senses into one table."

№ классов 1)	Наименование классов 2)	Характеризующие породы 3)	4) Временное сопротивление сжатию, кг/м²	f	5) Примечание
I	a) Весьма крепкие	b) Кварцит	3000	20	c) Порохострельные работы
II	a) Крепкие	b) Гранит и граувакка	1500	10	
III	Довольно крепкие a)	Крепкий песчаник, известняк b)	900	6	
IV	Средней крепости a)	Крепкий глинистый b) сланец, мягкий песчаник, крепкий уголь	600	4	
V	Довольно слабые a)	Мягкий сланец, мягкий уголь b)	300	2	Кайловая работа c)
VI	Слабые породы a)	Глина, сырой песок b)	—	1	
VII	Сыпучие породы a)	Сухой песок, осыпи b)	—	0,7	Лопатные работы c)
VIII	Плывучие a)	Плывун b)	—	0,1—0,3	Вычерпывание c)
IX	Вода a)	Вода a)	-	0	

Table. KEY: 1. No. of classes; 2. name of classes; 3. characteristic rocks; 4. ultimate resistance to compression kg/m²; 5. note; I - a. quite strong; b. quartzite; c. blasting; II - a. strong; b. granite and graywacke; III - a. rather strong; b. solid sandstone and limestone; IV - a. average strength; b. solid clay slate, soft sandstone, hard coal; V - a. rather weak; soft slate, soft coal; c. pick work; VI - a. weak rocks; b. clay, wet sand; VII - friable rocks; b. dry sand, talus; c. shovel work; VIII - a. running; b.

quicksand; c. dredging; IX - a. water.

1) Классы крепости	2) кг/см²	f	3) Добывание		6) Бурение шпуров		7) Взрывные работы	9) Оседание поверх ности	10) Крепление и целики
			4) Ржиха	5) Долежалек	4) Ржиха	5) Долежалек	8) Шалон	4) Ржиха	11) автор
I	3000	20	20	—	18	—	13,3	—	—
II	1500	10	11	10	12	12	10,7	10	10
III	900	6	7	7	6	6	6,7	6	6
IV	600	4	4,8	4	—	4	4	4	4
V	300	2	1,7	2	—	—	2	2	2
VI	—	1	1,1	1	—	—	—	1	1
VII	—	0,7	0,6	0,5	—	—	0,7	—	0,7
VIII	—	0,1—0,3	—	—	—	—	—	—	0,1—0,3
IX	—	0	—	—	—	—	—	—	0

Table. KEY: 1. classes of strength; 2. kg/cm^2; 3. recovery; 4. Rzhikha; 5. Dolezhalek' 6. drilling of blastholes; 7. blasting; 8. Shalon; 9. sinking of surface; 10. support and pillars; 11. author.

It is easy to see that the data of various authors and for different concepts of strength are close to each other, almost to the point of complete identity, which cannot be explained by chance and one must see the confirmation of the correctness of our conclusions concerning the possibility of a single, rational classification with respect to the strength coefficient."

From the excerpts given above it is evident that even in his first works, in the area of study of rock strength M. M. Protod'yakonov drew all of the basic conclusions concerning this problem: 1) he showed that various indices of relative strength of rocks practically do not differ from each other; 2) provided a measure of relative strength of rocks - the strength coefficient; 3) divided all rocks into several classes with respect to the value of the strength coefficients.

In subsequent works M. M. Protod'yakonov supplemented, expanded and refined the work performed in this area. Thus, he increased the number of classes from eight to ten and for some classes introduced an additional subclassification which considerably expanded the quantity of comparable data showing the practical identity of various classifications.

In proportion to the accumulation of data he refined several times the relationship between the ultimate resistance of rock to uniaxial compression and the strength coefficient.

The generally known version of the table of rock strength coefficients and its more complete bases are given in the book by M. M. Protod'yakonov [3], the first chapter of which is given in the first section of this collection.

Among the supporters and followers of M. M. Protod'yakonov there exists a rather widespread, although simplfied interpretation of the values of the strength coefficient. They usually consider that the strength coefficient f is one hundredth of the ultimate resistance of rock to uniaxial compression and forget completely about its other connections. This definition is correct but at the same time it is

incomplete and imprecise. M. M. Protod'yakonov considered that the strength coefficient of rock is the average relative strength of rock determined by several different methods.

Thus, he wrote [3]: "Various methods are suitable for determination of the strength coefficient of rock. From what has been said it is evident that for this we may use the values of any ultimate resistance, or what is even better, the averages of various ultimate resistances. We may also use the quantity of expended labor during various mining operations, the required quantity of explosive, pressure produced by one or another rock, and so forth."

Making a selection from M. M. Protod'yakonov's table [3] for one class of strong rocks we obtain:

Method of Destruction; Strength Coefficient

uniaxial compression of cubes in a press; 9.4-10.0

recovery using the Rzhikha method; 10.0

recovery using the Dolezhalek method; 10.0

manual drilling according to the description of the Donets basin; 10.0

drilling with pneumatic hammers; 11.2

pressure on timbering according to Protod'yakonov; 10.0

sinking of the surface according to Rzhikha; 10. 0

dressing of stones according to the Urochnyy position; 10.0-12.2

drilling with pneumatic hammers according to the description of the Donets basin; 10.7-11.2

Average; 10.0

From these data it is possible to confirm that M. M. Protod'yakonov considered: if a rock is stronger than the standard in one ratio by 9.4 times and in another ratio by 10 times, and in a third by 11.2 times, etc. then in general it is stronger than the standard by approximately 10 times. He used this number 10 as the strength coefficient which was common for the entire given group of rocks.

In Fig. 1 the axis of the abscissa shows the average values of the strength coefficient f which were employed by M. M. Protod'yakonov, and on the axis of ordinates the values of the same coefficients obtained by him by processing data of a number of researchers with the various methods of destruction mentioned above. We connected all points for each method of destruction with each other. As we see, all lines intertwine closely together and move in a single common bundle. The line of average values of the strength coefficient passes exactly through the middle of this bundle.

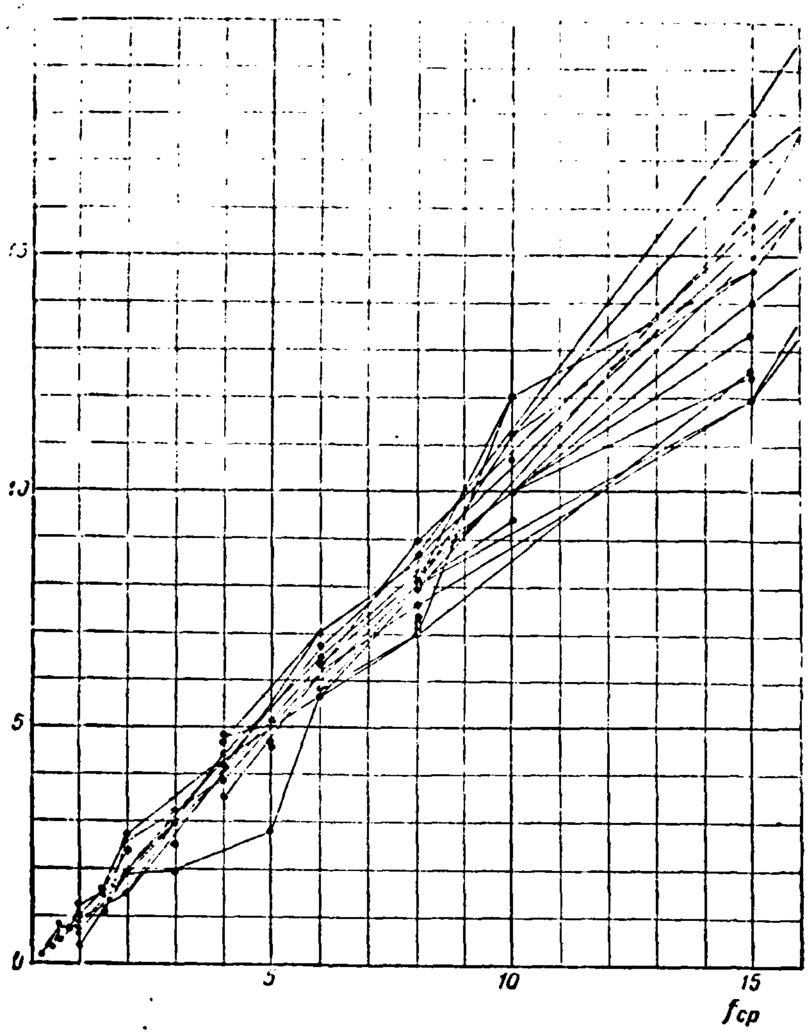

Fig. 1. Relationships of individual and average values of strength coefficients according to the data of Prof. M. M. Protod'yakonova.

Taking the average values instead of the individual values of strength coefficients M. M. Protod'yakonov replaced the entire bunch with a single straight line. Let us try to evaluate the deviations of individual values of strength coefficients from their common average values. For this we select limits of fluctuations of the strength coefficients with respect to various methods of destruction and calculate the values of coefficients of a variation for each class of strength of rocks. As a result we obtain:

1) f по разным методам	2) f по Протодьяконову	3) Коэффициент вариации, %
0,2	0,2	—
0,4—0,6	0,5	20
0,5—0,8	0,6	22
0,7—0,8	0,8	14
0,4—1,2	1,0	26
1,1—1,6	1,5	13
1,5—2,7	2,0	15
2,0—3,2	3,0	12
3,5—4,8	4,0	9
2,8—5,0	5,0	19
5,6—7,0	6,0	[illegible]
7,0—8,8	8,0	7
10,0—12,2	10,0	8
12,0—18,0	15,0	12
18,0—26,0	20,0	13
4) Среднее . . .		14

KEY: 1. f according to various methods; 2. f according to Protod'yakonov; 3. coefficient of variation; 4. average.

As we see, the deviations are estimated by coefficients of variation from 7 to 26 $^0/_0$ and on the average comprise 14$^0/_0$. A similar difference does not exceed the difference from heterogeneity

of rock in one and the same stope [5]. In this case it is also necessary to consider that M. M. Protod'yakonov compared data from published works of various authors. Rocks of the same kind tested by different authors did not necessarily have precisely identical properties. But even under these conditions the deviations had a permissible value. Therefore, if different methods of breakdown for determining the strength coefficients were actually employed on the same rocks then the deviations would be even less. M. M. Protod'yakonov was able to note the connection between various classifications because he took a sufficiently wide range of change of the strength of rocks and a large volume of data.

Replacement of the individual values of the strength coefficients by averages enabled M. M. Protod'yakonov to establish the common, typical, and main differences of rocks from each other. Disregarding the individual, secondary differences of mechanical properties of rocks which only clouded the general picture and made understanding of the problem difficult, he significantly simplified matters.

Precisely the significance and the simplicity of the strength coefficients proposed by M. M. Protod'yakonov have made them so widely used in practice.

M. M. Protod'yakonov wrote [3]: "Numbers, expressing the relative strength of rock will be "strength coefficients" and their most important property is that they make it possible to compare rocks with each other without knowing what stresses there are in them and how they are brought about." Consequently, strength, as understood by M. M. Protod'yakonov is an objective property of rock which depends only on itself and does not depend on the process of destruction in which it is manifested.

This thought is presented most clearly in another part of the same work [3]: "If a rock is stronger than another by a certain number of times in some respect, for example during drilling, then it will be the same number of times stronger in any other respect, for example during blasting, with respect to the pressure on timber, and so forth." M. M. Protod'yakonov noted repeatedly that the equality of strengths is approximate.

After M. M. Protod'yakonov's death attempts were made to refute his strength coefficients and the scale of rock strengths. Prof. A. F. Sukhanov cited such arguments as the fact that clay is easy to drill but difficult to blast while granite is equally difficult to drill and blast. For the two classes of rocks the difference in the expenditure of explosives is not proportional to the difference in the quantity of blastholes per unit of volume.

The effect of replacement of steel drills by Pobedit ones is not identical in the two rocks.

On the basis of these examples A. F. Sukhanov concluded that the coefficients of drillability and blastability are not equal and are not proportional to each other and therefore the strength coefficients of M. M. Protod'yakonov are not founded and contradict reality. He recommended proceeding to establish individual classifications: borability, blastability, separation, and so forth and rejecting the concept of strength [6].

In essence this conclusion suggests returning to the position in the evaluation of rock strength which existed before M. M. Protod'yakonov.

For checking the conclusions of A. F. Sukhanov let us use the classification of rocks with respect to borability and blastability which he suggested. At the end of his work [6] A. F. Sukhanov gives a consolidated table (32) of various indices of mechanical properties of rocks.

The coefficient of relative strength of rocks in this table is

equal to

$$f_1 \approx 0.01\ H_1$$

where H_1 is the ultimate resistance of rock to uniaxial compression in kg/cm².

Calculation of the coefficients of strength of rocks on the basis of production indices of their drillability and blastability using the final formulas of M. M. Protod'yakonov was not possible since the current indices obtained by A. F. Sukhanov refer to new types of drilling hammers with a different operation of the hammer and to new types of drills reinforced with cermet hard alloys, and to new types of explosives which did not yet exist when M. M. Protod'yakonov was working.

However, following the path of M. M. Protod'yakonov it is easy to find new empirical formulas which have the same structure and differ only by numerical coefficients. For example, graphically comparing the drilling time of blastholes using reinforced bits (min/m) with M. M. Protod'yakonov's strength coefficients given in the same table [6, Table 32] it is possible to find that they are practically equal to each other:

$f_2 \cong H_2$.

In the same manner we find the following empirical formulas:

$f_3 \cong 0.15 H_3$;

$f_4 \cong 4 H_4$,

where H_2 - drilling time for 1 m of blasthole with reinforced bits, min;

H_3 - specific work of drilling blastholes, kg/cm³;

H_4 - specific expenditure of ammonite No. 2, kg/m³.

In view of the fact that the ratio between the strength coefficient and the specific expenditure of bits, according to M. M. Protod'yakonov, has an exponential form, we also find this dependence graphically, but not in the conventional system of coordinates but on a double logarithmic grid. Then we obtain

$$f_6 \cong 2{,}8\sqrt{Z},$$

where Z - specific expenditure of reinforced bits, pieces/m.

Let us designate by f the coefficients of strength of M. M. Proto'dyakonov, which are given in the table by A. F. Sukhanov.

Summarizing all of the results in Table 1, we find:

Table 1

H_1	f_1	H_2	f_2	H_3	f_3	H_4	f_4	Z	f_5	f	f_{cp}
3500	35,0	35,0	35,0	250	37,0	8,3	33,0	1,00	28	—	31,0
2500	25,0	25,0	25,0	175	26,0	6,7	27,0	0,75	24	—	25,0
2000	20,0	20,0	20,0	140	21,0	5,3	21,0	0,50	20	20,0	20,0
1700	17,0	17,0	17,0	120	18,0	4,2	17,0	0,35	17	18,0	17,0
1300	13,0	13,0	13,0	90	13,0	3,8	15,0	0,23	13	15,0	14,0
1100	11,0	11,0	11,0	70	11,0	3,0	12,0	0,15	11	12,0	11,0
900	9,0	9,0	9,0	63	9,0	2,4	10,0	0,10	9	10,0	9,0
800	8,0	8,0	8,0	49	7,0	2,0	8,0	0,07	7	8,0	8,0
600	6,0	6,0	6,0	35	5,0	1,5	6,0	0,05	6	6,0	6,0
500	5,0	5,0	5,0	31	5,0	1,2	5,0	0,04	6	5,0	5,0
400	4,0	4,0	4,0	28	4,0	1,0	4,0	0,03	5	4,0	4,0
300	3,0	3,3	3,3	23	3,5	0,8	3,2	—	—	3,0	3,2
200	2,0	2,7	2,7	19	2,8	0,6	2,4	—	—	2,0	2,4
150	1,5	2,0	2,0	14	2,1	0,5	2,0	—	—	1,5	1,8
100	1,0	1,7	1.7	10	1,5	0,4	1,6	—	—	1,0	1,4
80	0,8	1,3	1,3	7	1,1	0,3	1,2	—	—	0,8	1,0

Plotting f_1, f_2, f_3, f_4, f_5, f, and f on a graph (Fig. 2) we obtain a narrower bunch of lines which interweave more closely than in Fig. 1.

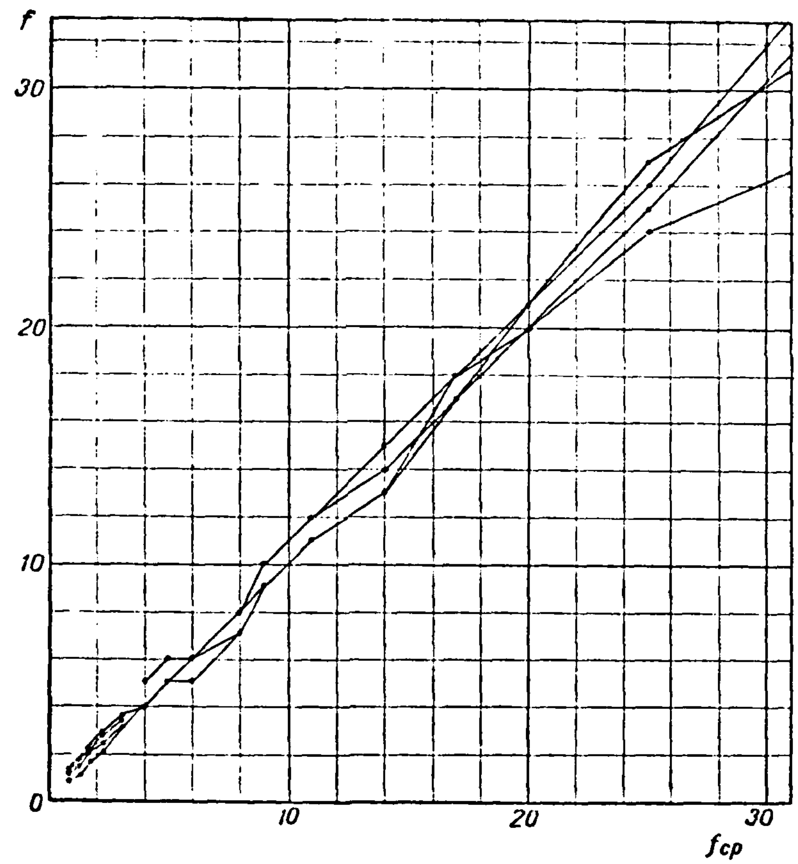

Fig. 2. Relationship of individual- and average values of strength coefficients according to the data of A. F. Sukhanov.

Calculating the limits of fluctuations of f and the variation coefficients v ($^0/_0$), we find

f_{cp}	f	v, %	f_{cp}	f	v, %
1,0	0,8–1,3	21	9,0	9–10	9
1,4	1,0–1,7	24	11,0	11–12	6
1,8	1,5–2,1	17	14,0	13–15	8
2,4	2,0–2,8	16	17,0	17–18	3
3,2	3,0–3,5	7	20,0	20–21	3
4,0	4–5	11	25,0	24–27	5
5,0	5–6	9	34,0	28–37	10
6,0	5–6	7			
8,0	7–8	8		1) Среднее	10

KEY: 1. average.

As we see the difference between the strength f, determined with various methods of destruction ($V_{cp}=10^0/_0$, $v_{макс}=24^0/_0$), turned out to be less than for M. M. Protod'yakonov and less than that obtained when repeating the tests using the same method in a stope (due to heterogeneity of the rocks).

Thus, the data of A. F. Sukhanov not only did not refute, but rather, brilliantly confirmed the view of M. M. Protod'yakonov

concerning the unity of strength coefficients with various processes of breakdown.

In concentrating his attention on individual deviations from a general law, Prof. A. F. Sukhanov did not notice the law itself.

Supporters of the individual independent technological indices (cuttability, drillability, blastability), A. F. Sukhanov, Ye. M. Montlevich, and others made a number of errors in attempts to refute the views of M. M. Protod'yakonov experimentally.

Thus, for example, in comparing cuttability and drillability of two seams of coal and having discovered that the layer which was difficult to cut was easier to drill, and vice versa, the layer which was easy to cut was difficult to drill, they concluded that in general there is not, and there cannot be, any kind of connection. In this case they lost sight of the fact that cutting is done in the base of the seam and the drilling of blast holes is done through its thickness, i.e., with respect to different benches of the seam. Meanwhile it has become known that the strength of various benches of one and the same seam may be quite different. In one seam the cutting zone may be stronger than the bench in which blastholes are being drilled, and in the other vice versa. Therefore researchers comparing two different methods of determining strength made a gross error in

assuming identical strength of all benches of a single seam. In essence, they compared indices under completely different, incomparable conditions.

Another error which is often made by these researchers is that they compare two methods of determining the strength of only two rocks, which differ little in strength and with a limited volume of data. At the same time they did not go beyond the zone of data spread brought about by heterogeneity of the rocks, where in general it is impossible to establish any kind of law.

Using the data of Table 1 let us compare the indices of borability f_3 and f_4 in two adjacent classes of rocks, for example in rocks of classes I and II according to A. F. Sukhanov. Then we obtain:

1) Класс пород	f_3	f_4
I	37	33
II	26	27

KEY: 1. class of rocks.

As we see, for rock of class I the drillability is greater than blastability by 1.12 times and for rock of class II, vice versa, it is less by 0.96 times.

If we limit ourselves to this data only (which some researchers usually did) one can come to the incorrect conclusion that these two methods of determination of strength are not comparable (drillability and blastability of rock).

But if instead of two adjacent classes of rocks, differing from each other only by 1.2-1.4 times, we take the entire gamut of rocks differing in strength by 28-34 times and plot the values f_3 and f_4 on a diagram (Fig. 2) then we notice the presence of a fully defined correlation between both indices. In this case it becomes clear that in the entire wide range of change of the strength of rock, which exceeds by several times the spread of data, there exists a practical equality of f_3 and f_4. The greater the number of experimental points and the broader the range of tested rocks, the clearer the connection of various indices with each other. The error of the researchers mentioned above consists in the fact that they try to find a functional - precise connection, where there actually exists only an approximate correlation connection.

In connection with the assertion of M. M. Protod'yakonov concerning the fact that: "If any rock is stronger than another a certain number of times in one respect, for example during drilling,

then it will be the same number of times stronger in any other respect, for example during blasting, with respect to pressure on timber, and so forth," we should not conclude that in general between all indices of mechanical properties of coals and rocks there must be a direct proportionality.

In the opposite case, without having established a direct proportionality between any two indices of mechanical properties of rocks one may conclude the absence of any connections between these indices, which refutes the concept of M. M. Protod'yakonov about the unity of strength coefficients of rocks during various processes of their destruction.

However, from the works of M. M. Protod'yakonov it follows that to the strength coefficient are directly proportional not all, but only those indices which in one or another form represent the specific work of destruction (under constant conditions of destruction). For example, indices of the specific expenditure of the tool are proportional to the strength coefficient in the second power, the indices of intensity of the processes of breakdown are inversely proportional to the strength coefficient f. Prof. M. M. Protod'yakonov nowhere speaks of proportionality of all constants to each other, but speaks of equality of the strength coefficients during various processes of breakdown.

Let us explain this with an example. According to the data of Table 1 let us take the values of Z and f_5 for various classes of rocks:

1) Класс породы	Z	f_5
I	1,00	28
XI	0,03	5

KEY: 1. class of rock.

and let us take the ratio of these indices to each other. For rock of strength class I the ratio will be equal to 28:1=28, and for rock of class XI 5:0.03=167, i.e., six times greater.

This is quite understandable and does not require explanation because the ratio of squares of the two values is not equal to the ratio of their first powers at all. At the same time the strength coefficients f_5, calculated on the basis of the specific expenditure of bits Z according to the empirical formula given above: $f_5 \simeq 2,8 \mid Z$, turn out to be practically the same as the strength coefficients obtained by another method.

Let us repeat that the position of M. M. Protod'yakonov speaks not about the direct proportionality of all indices to each other but

about the correlation connection of all indices of mechanical properties of rocks with each other.

The form of such a connection for each specific process of destruction and strength index may be easily established graphically in the presence of data for a wide range of rocks with respect to strength. Using the obtained graphs or empirical formulas it is possible to find an approximate value of the strength coefficient with respect to any characteristic of mechanical properties of rocks during any process of breakdown. The strength coefficients found in this manner during various processes of breakdown are practically equal to each other in spite of the absence of a direct proportionality between some of the initial indices. The difference between the strength coefficients determined by various methods does not exceed the difference during repetition of the tests with the same method.

It is necessary to note cases when, in fact, the strength coefficients of rock obtained during different processes of breakdown differ considerably.

Prof. M. M. Protod'yakonov wrote: "...it is necessary to be very careful with the determination of f in certain cases and its value may not be identical in various respects. Example. Let a given

granite, being strong (f=10) be broken by strong cleavage. For drilling blast holes this is not significant and therefore the value of f must be accepted as indicated. But it is obvious that during blasting such granite easily breaks into pieces and a small quantity of explosive is required and therefore in this case f should be taken smaller, for example 8 or 6, depending on the circumstances."

Subsequently M. M. Protod'yakonov emphasized that in individual cases there may be deviations from the general law.

Summing up what has been said on the problem of the strength of rocks we may note the following:

1. Errors of researchers, opponents of M. M. Protod'yakonov, consisted in the fact that in comparing indices they overlooked the difference in the strength of various benches of one and the same seams and sought functional connections there where correlation connections existed, and sought to find a direct proportionality there where there existed other types of dependence; they concentrated their attention on specific, secondary differences instead of on basic, general features and connections.

2. Graphic comparison of the data of supporters of independent technological indices of mechanical properties of rocks leads to the

conclusion of the presence of correlation connections between these indices, which confirms the viewpoint of M. M. Protod'yakonov. Using equations of these connections it is possible to move from any index of mechanical properties of rocks to strength coefficients and vice versa.

3. Unity of the strength coefficients f during various processes of breakdown is a basic law established by numerous experiments in a wide range of strength of rocks. The difference in the strength coefficients during various processes of breakdown is a deviation from the basic law. It bears a partial, secondary character and is manifested in a narrow range of change of strength.

4. Use of single coefficients of strength f makes it possible to compare and to generalize data on various types of breakdown. When using a number of independent indices scientific generalizations are not possible. At the same time the use of one index, the coefficient of strength f, in practice is considerably simpler than several independent indices.

Analysis of the structure of numerous empirical formulas obtained by M. M. Protod'yakonov by processing mine data [3] makes it possible to join the overwhelming majority of them into three basic groups:

(1) $$f \simeq k_1 H;$$

(2) $$f \simeq \frac{k_2}{V};$$

(3) $$f \simeq k_3 \sqrt{Z},$$

where f - coefficient of strength;

H - specific work of breakdown;

V - productivity of the means of breakdown;

Z - specific expenditure of tools;

k_1, k_2, k_3 - numerical coefficients of proportionality.

The values entering into the formulas, which were expressed by M. M. Protod'yakonova often are not in the names indicated above but their physical sense is the same as that given by us above.

For example, value H may be expressed not only by kg/m³, but also by the number of man/shifts expended on breaking down 1 ton of

coal or rock, the expenditure cf compressed air for drilling 1 running meter of blast hole, the specific consumption of explosives in kg/t, and so forth. In this case only the numerical values of the coefficient k will change.

Value V with a constant power of the means of breakdown is expressed through values of the rate of passago or drilling, the productivity of excavation workers (t/h or t/shift) the rate of feed of machines, etc.

Designating:

W - power of the means of breakdown;

T - time of breakdown;

U - broken down volume;

A - expended labor;

N - expenditure of tools, we obtain

$$H=\frac{WT}{U};\ V=\frac{U}{T};\ Z=\frac{N}{U};\ A=WT.$$

Substituting values, we find that the three formulas given above

may be reduced to two formulas:

(4) $$f=\frac{k_1 W T}{U};$$

(5) $$f=k_3\sqrt{\frac{N}{U}}.$$

Expressions (4) and (5) are valid with various processes of breaking down rocks (cutting, breaking, drilling, blasting, etc.), i.e., they reflect certain objective general laws of processes of break down.

Consequently, applying these expressions during the study of new processes and means of breakdown which were not investigated by M. M. Protod'yakonov, it is possible to expect to obtain correct results. Actually, the basic laws, established for the first time by M. M. Protod'yakonov, were later constantly used in various modifications by many researchers.

From formula (4) it follows that with a constant power of the means of breakdown W, the coefficient of strength f is directly proportional to the specific energy of breakdown H=A/U. It turned out that the indices of strength of coals (suggested by the Institute of Mining of the Academy of Sciences, USSR and BUGI), based on the measurement of the specific energy of breakdown, are directly

proportional to the coefficients of strength of M. M. Protod'yakonov.

It is known that not a single process of breakdown may occur without the expenditure of energy, and consequently the specific energy is a universal physical index, characterizing the mechanical properties of rocks under constant conditions of breakdown. The presence of a direct proportionality between relative and dimensionless coefficients of strength of M. M. Protod'yakonov and the specific energy of breakdown is a quite important factor which explains why the coefficients of strength f reflect so well the various mechanical properties of rocks during breakdown and are firmly rooted in the practice of mining.

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